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## A CONCEPT OF LACEY'S REGIME THEORY

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# A CONCEPT OF LACEY'S REGIME THEORY

Ning Chien,[1] A.M. ASCE

## SYNOPSIS

Lacey's regime theory is analyzed on the basis of the Einstein bed-load function. It has been found that within the limits of the observed flows on which the regime theory was derived, the "silt" factor $f_{VR}$ depends on the sediment concentration of the channel flow while $f_{RS}$ is a function of the bed material size. Using these functional relationships between sediment characteristics and Lacey's "silt" factors, the depth and slope of an alluvial channel in regime can be determined either by the Einstein bed-load function or by Lacey's regime theory, with practically no difference between the two. The use of the regime theory for other than conditions in India and Pakistan should be executed with great care since the "silt" factor $f_{VR}$ then depends also on the characteristics of the flow.

## INTRODUCTION

In northern India and Pakistan the rainfall, except at monsoon seasons, is generally not sufficient for the growth of crops. On the other hand, large rivers, coming out of the Himalaya Mountains, spread over the plains and carry discharges comparable to that of the Mississippi. The great demand of water for agricultural purposes combined with an ample supply of river water make this part of the Indian plains the ideal place for an extremely high development of irrigation. The water coming out of the mountains are often heavily charged with sediment and the rivers—the Indus and the Ganges —flow today through an alluvial plain which was deposited by the two rivers during the recent geologic periods. On some of the irrigation projects enormous sums were spent for maintenance work because of the continuous silting up of the channels. Engineers then realized that certain natural laws must exist which control the characteristics of channels able to carry given discharges and sediment loads without excessive aggradation or degradation. Lindley (1), for instance, stated in 1919 that

> "--- the dimensions, width, depth and gradient of a (regime) channel to carry a given supply loaded with a given silt charge were all fixed by nature."

Since the end of last century, various efforts, mostly under the direction of British engineers, have been made in seeking for an understanding of the natural processes. The most successful of those was by Gerald Lacey who developed a complete set of formulas for the determination of width, depth, and slope of the channels in regime (2)(3)(4). This theory now bears his

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name and has been used quite extensively in India and Pakistan for the design of irrigation canals. Attempts have been made by some of his followers (5) (6)(7) to improve the theory, but the basic equations as proposed by Lacey remain essentially the same, although they may be expressed in different forms with different interpretations.

The development of Lacey's regime theory is based on a great mass of data and experience, and for that alone the theory deserves due recognition. Yet, on the other hand, neither does the theory give a clear description of the physical picture involved in the problem nor does it define what actually governs the characteristics of an alluvial channel. Without knowing these the hesitation of engineers to apply Lacey's theory to conditions different from those prevalent in India and Pakistan is surely apprehensible. The formulas as proposed by Lacey also involve factors which are based essentially on experience alone, making the use of the theory difficult for those who lack this experience. It is the purpose of this paper to evaluate quantitatively these factors in terms of the physical conditions imposed on the channel, and to show the possible limitations of Lacey's regime theory.

## Lacey's Regime Theory

Lacey's regime theory can be expressed in terms of the following three independent equations:

$$V^2/R = 1.325\, f_{VR} \tag{1}$$

$$R^{\frac{1}{3}}S^{\frac{2}{3}} = 0.0052\, f_{RS} \tag{2}$$

$$p = a\, Q^{\frac{1}{2}} = 2.67\, Q^{\frac{1}{2}} \tag{3}$$

where

$V$ = average velocity of the flow
$R$ = hydraulic radius of the channel
$S$ = channel slope
$p$ = wetted perimeter of the channel
$Q$ = discharge
$f_{VR}$ and $f_{RS}$ = "silt" factors

$f_{VR} = f_{RS}$ as given in Lacey's original works, but since then they have been shown to be different. Eqs. (1) to (3) can be applied only to channels which contain a bed of loose sediment of the same type that is moved along the bed, and which are essentially at equilibrium. From these basic equations many other correlative relationships also can be derived.

## Basic Premises

The basic conception of this paper is built on the following premises. The first two concern the behavior of alluvial channels in general, and the second two deal with Lacey's theory in particular.

1) The equilibrium state of an alluvial channel is attained by adjusting the dimensions of the cross section and the slope of the channel in accordance with the conditions imposed on the channel by the drainage basin. These conditions, which are independent of the channel itself, include the sediment inflow, the discharge, and the gradation and size of the material which

composes the channel bed and the banks. It has long been recognized (8) that the sediment inflow is a primary factor governing the stability of an alluvial channel.

2) The alluvial channel differs from the fixed-boundary channel by the fact that the boundary is molded by the flow and may change with the flow. The frictional resistance of an alluvial channel flow cannot be described generally by one formula with universal constants, such as the Manning's formula. It must be interpreted as a composite effect of the following parts:

a) resistance of the sediment grains which compose the channel bed;
b) resistance of banks; and
c) resistance of sand bars and other irregularities;

each of which follows different and independent laws.

3) Eqs. (1) to (3) are empirical relationships based on field observations only. They should not be visualized as fixed laws with universal application.

4) Lacey's regime theory is the product of sixty years' experience gathered in India and Pakistan, and it serves today as a useful tool in designing irrigation canals in that area.

## Method of Approach

It is not the intention of this paper to rationalize eqs. (1) to (3) by scrutinizing the physical significance of each formula. Rather it is proposed to offer a philosophical basis of Lacey's regime theory by pointing out why the sediment load is not included in the theory.

The omission of the sediment load as an explicit variable in eqs. (1) to (3) can be explained by either of the following two possibilities:

1) the "silt" factors in eqs. (1) and (2) actually include implicitly the sediment load together with the bed material size;

2) although the dimensions and the slope of an alluvial channel must depend on the sediment inflow, a certain combination of these variables may depend very little on the sediment load.

In testing these hypothesis, the graphical solutions as given by the writer (9) in relating the channel depth and slope with the unit discharge and sediment load are taken as the basis of analysis. These graphical solutions are constructed according to the Einstein bed-load function (10), the only working tool available at the present which gives a complete description of the alluvial channel flow and the sediment transport.

## Conditions under Which the Regime Theory Was Developed

The physiographical and climatic conditions in northern India and Pakistan are described in reference 6. The following is the range of variables used by Lacey in his analysis which is determined by taking the central 90% of the cumulative frequency curve of each variable (11):

By far the main source of data used by Lacey and others comes from field observations on existing irrigation canals which proved to be in equilibrium. For this part of the information, the range of bed material size is particularly limited.

## Results of Analysis

The Analysis was carried out in different steps. First, the bank friction

TABLE 1

Range of Variables Under Which the Regime Theory Was Developed

| Variable | Unit | Canal Data | | | River Data | | |
|---|---|---|---|---|---|---|---|
| | | Punjab | Sind | Total | Punjab | Misc. | Total |
| Velocity | fps | 1.5-2.8 | 1.5-2.9 | 1.5-3.0 | 2.0-13.5 | 2.4-7.5 | 2.0-7.6 |
| Hydraulic Radius | ft | 1.1-8.0 | 1.6-11.0 | 1.2-10.3 | 2.5-13.3 | 3.1-15.3 | 3.0-15.6 |
| Slope | parts /1000 | 0.05-0.33 | 0.05-0.14 | 0.05-0.35 | 0.10-0.57 | 0.13-1.72 | 0.10-1.55 |
| Discharge | cfs | 20-4500 | 35-8500 | 20-6500 | - | - | - |
| Grain Size | mm | 0.20-0.38 | 0.05-0.15 | 0.05-0.33 | - | - | - |
| $f_{VR}$ | - | 0.6-1.5 | 0.4-0.8 | 0.4-1.5 | 0.5-3.5 | 0.4-6.0 | 0.5-6.0 |
| $f_{RS}$ | - | 0.6-1.5 | 0.5-0.8 | 0.5-1.5 | 0.6-2.5 | 0.8-6.0 | 0.6-6.0 |

was neglected and the conditions as given in Table 1 were investigated. This type of analysis was then extended to cover conditions different from those prevalent in India and Pakistan. And, finally, the bank friction was introduced and its effect studied.

1) First step

Conditions investigated:

Bank friction neglected

Bed material size = 0.25 mm. (average size of bed material in northern India and Pakistan)

Hydraulic radius: 2-25 ft.

Slope: 0.0001 - 0.0004

Results and interpretations: The "silt" factors, $f_{VR}$ and $f_{RS}$, are given in Fig. 1 in terms of the sediment concentration, $q_T/q$, in ppm. The calculated points can best be approximated by straight lines of the following forms:

$$f_{VR} = 0.061\ (q_T/q)^{0.715} \qquad (4)$$

$$f_{RS} = 1.18\ (q_T/q)^{0.052} \qquad (5)$$

where $q_T$ is the sediment transport rate (including both the bed-load and the suspended-load) per unit width and q is the discharge per unit width. While $f_{VR}$ depends strongly on the sediment load, is the combination of slope and hydraulic radius as given by eq. (2) practically independent of the sediment transport rate. On the other hand, as will be shown in the next section, $f_{RS}$ is a function of the bed material size. Within the range of grain sizes as given in Table 1, no relationship has been found linking $f_{VR}$ with the size of the material which composes the bed.

It is now clear that if Einstein's method is used in determining the depth and slope of an alluvial channel, a pre-requisite knowledge on the sediment inflow and the material in the bed is required. Even if the determination of sediment inflow to irrigation canals is by no means a simple matter (9), it is, nevertheless, a concrete matter with physical significance. The use of Lacey's regime theory involves the estimation of "silt" factors which, for the existing conditions in India and Pakistan, must represent functions of sediment load and size. Viewing the regime theory in this manner and by using Fig. 1, the two methods give practically the same results.

2) Second Step

Conditions investigated:

Bank friction neglected

Bed material size: 0.25 mm., 2.5 mm., and 25 mm.

Hydraulic radius: 2 - 30 ft.

Slope: 0.0001 - 0.0005 (for D = 0.25 mm.)
0.0003 - 0.0025 (for D = 2.5 mm.)
0.001 - 0.01 (for D = 25 mm.)

Results and interpretation: The relationships between the "silt" factors and the sediment concentration and size are given in Figs. 2-5. In Figs. 2 and 4, R is held constant and S varies. The reverse is true in Figs. 3 and 5.

In the wider range of variables, especially of the sediment size, the trend of $f_{RS}$ remains the same. With sediment size, D, as a

variable and expressed in mm., eq. (5) becomes

$$f_{RS} = 2.2\, D^{0.45}\, (q_T/q)^{0.052} \qquad (6)$$

for $q_T/q < 200$ ppm. The change of $f_{VR}$ with sediment concentration not only follows a somewhat different pattern, but also is quite erratic. For other than conditions in India and Pakistan, $f_{VR}$ depends also on the hydraulic characteristics of the channel. This makes the general application of Lacey's regime theory extremely difficult. It is not just the question of whether one has the proper training or experience in estimating the values of "silt" factors, but rather the experience gathered in northern India and Pakistan may fail to apply when the conditions are substantially different from those existing in that area.

3) Third Step

Conditions investigated:

Bank friction introduced with vertical side walls and Manning's n of 0.02 (assuming growth of soft vegetation along the banks)
Width of the channel as given by eq. (3)
Bed material size: 0.25 mm.
Hydraulic radius: 2-30 ft.
Slope: 0.0001 - 0.0005

Results and interpretations: The conclusions derived from the first two steps of analysis are obtained under the condition that the bank friction is ignored. It is important to ascertain whether the effect of bank friction will in any way materially modify these conclusions. The effect of bank friction depends on the roughness of the banks and the width-depth ratio of the channel. The selection of Manning's n of 0.02 for the bank roughness is of course arbitrary, but, nevertheless, representative. If the banks behave hydraulically smooth as suggested by Blench (6), the net results of the analysis should fall somewhere between what indicated in Figs. 2 and 4 and what given in Figs. 6 and 7. The use of eq. (3) in determining the channel width is justified as long as the range of variables are not significantly different from that listed in Table 1.

A comparison of Figs. 2 and 4 with Figs. 6 and 7 clearly demonstrates that the bank friction has little effect on the over-all trends according to which the "silt" factors vary with the sediment concentration. Only for small channels does the inclusion of bank friction result in a slight shift of the relative position of both the $f_{VR}$ and $f_{RS}$ curves.

Two remarks should be made here:

1) The sediment load used in this study refers only to the bed-material load, the material which has been found abundant in the bed. The actual sediment concentration of the canal flow, including that of the wash-load (12), may be considerably higher than the values given in Figs. 1-7.

2) In using Einstein's bed-load function, the effect of bar resistance is determined from river measurements (13). There is some evidence indicating that below a certain limit the bar resistance is affected by the width of the channel. In a narrow channel the bars do not develop to their full sizes, due to the confinement by the banks. This, in effect, will bring the values of $f_{VR}$ and $f_{RS}$ closer together at small sediment concentrations, but will not mater-

ially change the conclusions derived from the present analysis.

### Channel Width

The third relationship given by Lacey, which links the width of the channel to the discharge, cannot be appraised by comparing with the Einstein bed-load function, as it is beyond the scope of the latter. The reader is referred to a paper by Leopold and Maddock (14) in which the characteristics of a number of stream channels in the Great Plains and the Southwest of this country have been studied. They found that a functional relationship between p and $Q^{\frac{1}{2}}$ does exist among the various cross-sections along the length of the river under the condition that discharge at all points is equal in frequency of occurrence. As concerning the constant of proportionality a in eq. (3), which Lacey found to be 2.67, they say:

> "Lacey found so little variation of a in Indian regime canals that he considered it to be a constant for all streams. Inspection of the large differences in intercept of the lines in figure 9 representing natural rivers indicates that the value of a is not a constant."

Little is known today upon what a depends.

## CONCLUSIONS

The findings of this study are summarized as follows:

1) The "silt" factors in Lacey's regime theory have been correlated with the conditions imposed on the channel by the watershed according to the Einstein bed-load function.

2) For the channels in the Indian plain area from which the regime theory was originally derived, $f_{VR}$ depends on the sediment concentration of the flow while $f_{RS}$ varies primarily with the bed material size. Functional relationships between the "silt" factors and the sediment characteristics are given. Using these relationships, both the Einstein bed-load function and Lacey's regime theory give the same depth and slope of an alluvial channel in equilibrium.

3) The general application of Lacey's regime theory to other than conditions in India and Pakistan is questionable as $f_{VR}$ then depends also on the characteristics of the flow, making its selection extremely difficult.

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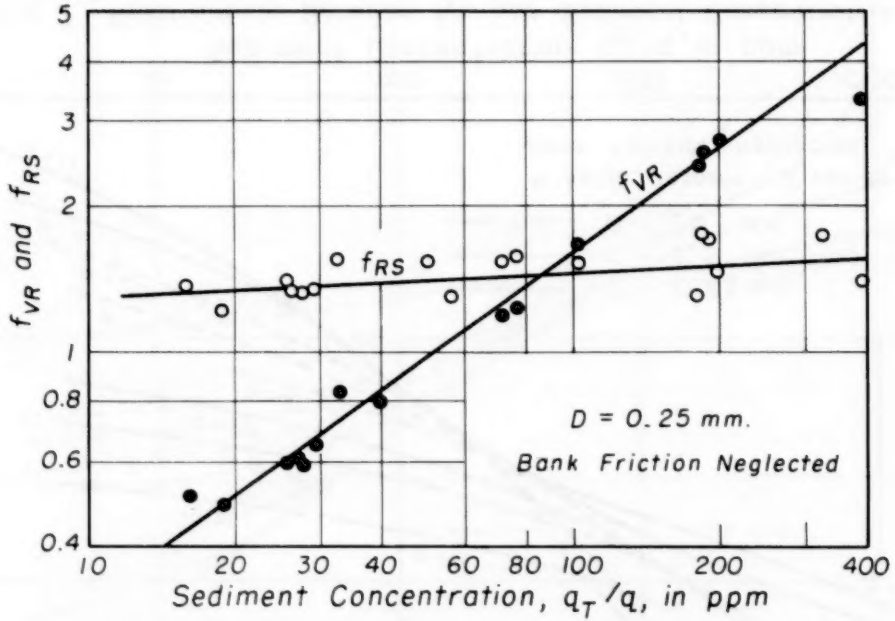


Fig. 1 Relationship Between "Silt" Factors And Sediment Concentration For The Conditions Prevalent in Northern India and Pakistan (Calculated According To The Einstein Bed-Load Function)

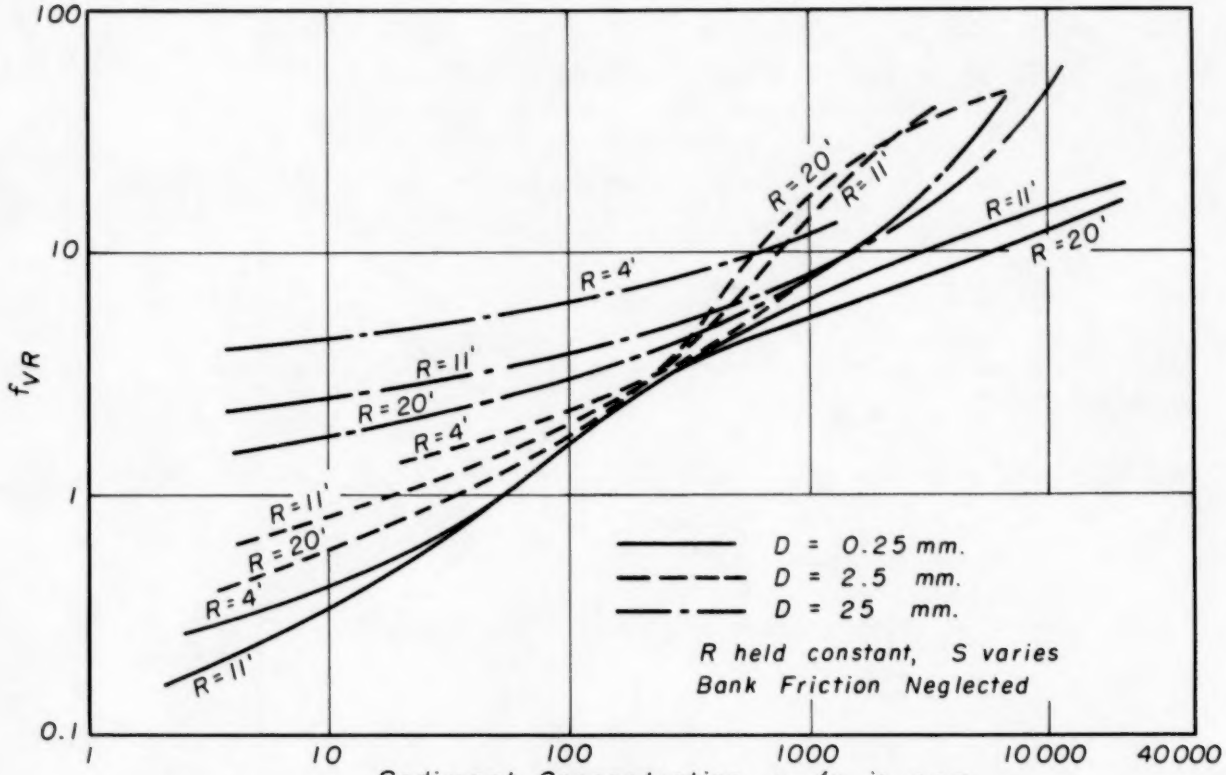


Fig. 2 Relationship Between $f_{VR}$ and Sediment Concentration For Wider Range of Conditions

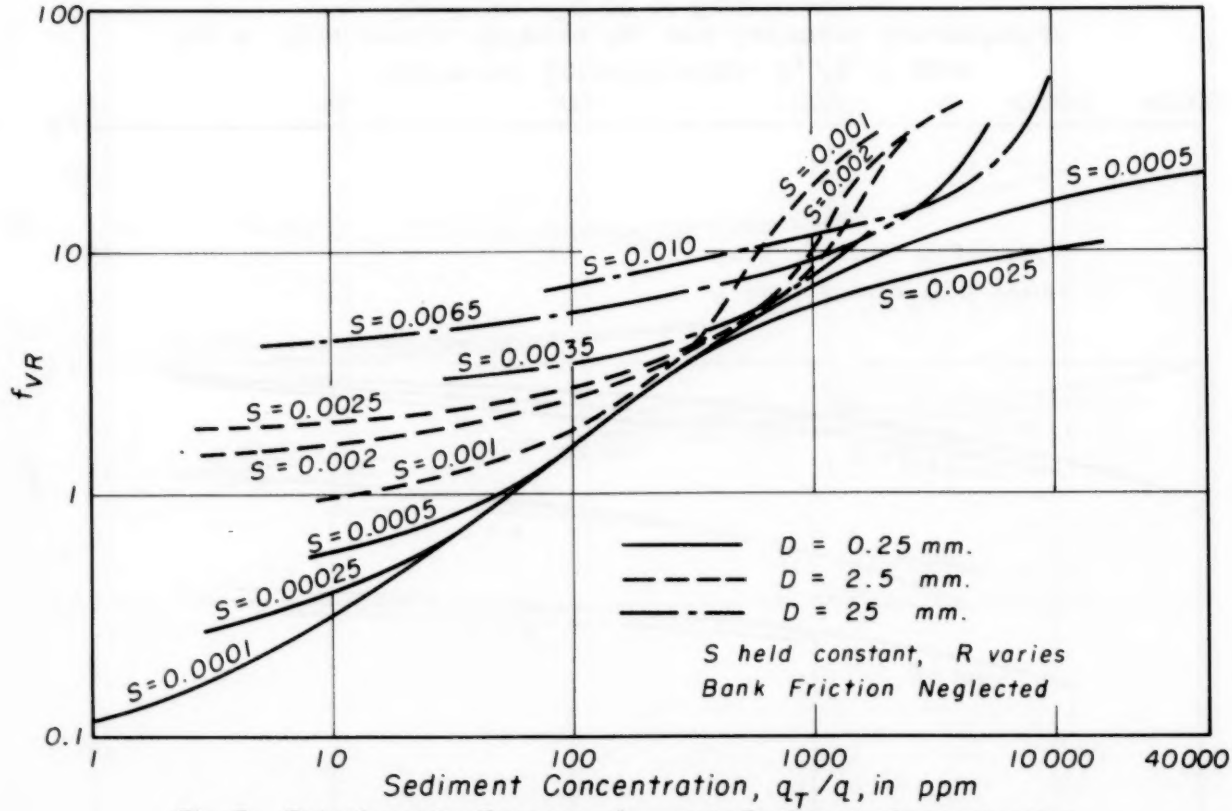


Fig. 3 Relationship Between $f_{VR}$ and Sediment Concentration For Wider Range of Conditions.

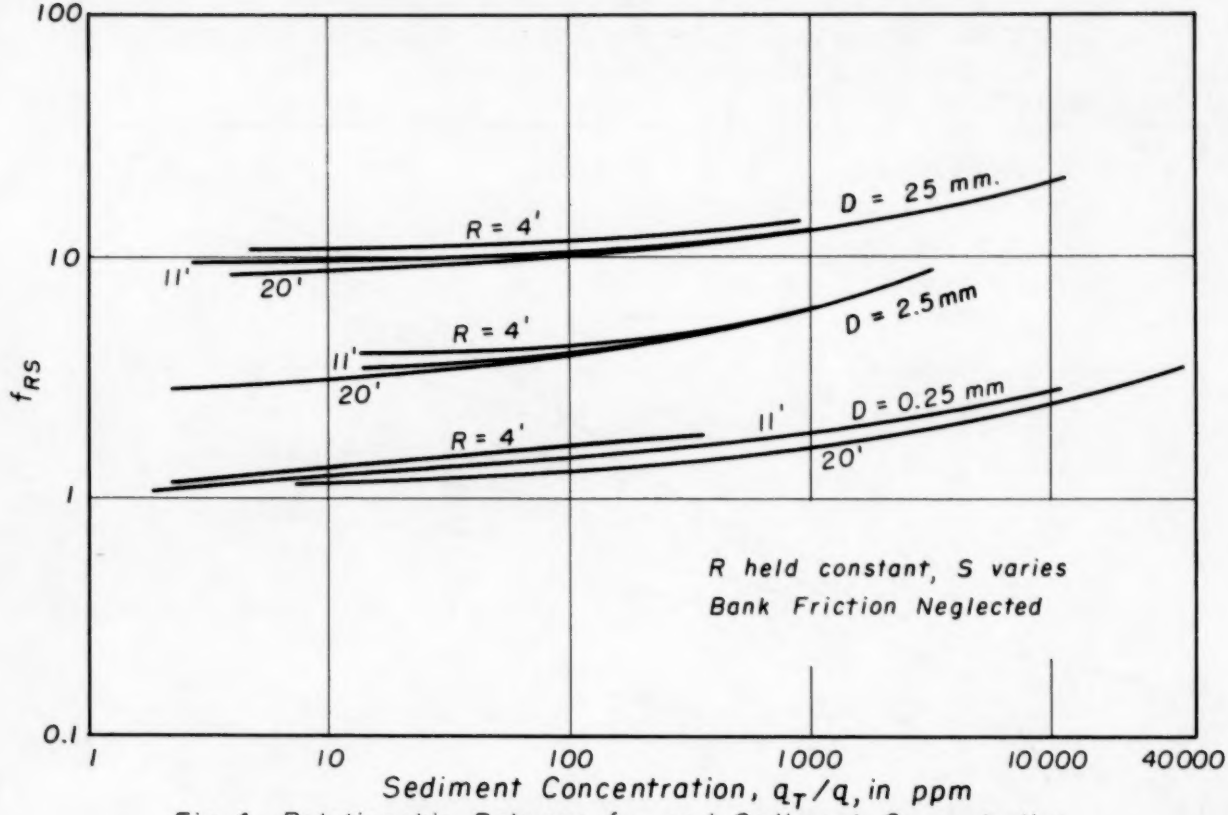


Fig. 4 Relationship Between $f_{RS}$ and Sediment Concentration For Wider Range of Conditions.

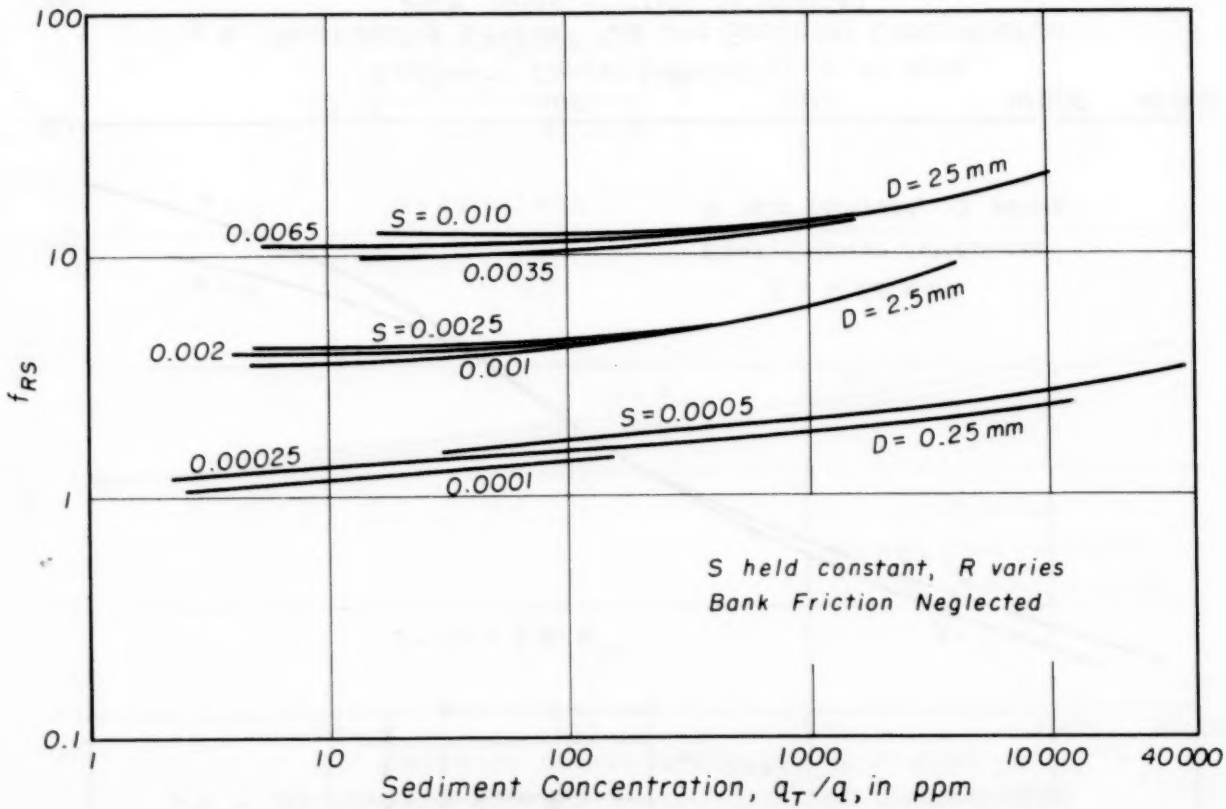


Fig. 5 Relationship Between $f_{RS}$ and Sediment Concentration For Wider Range of Conditions.

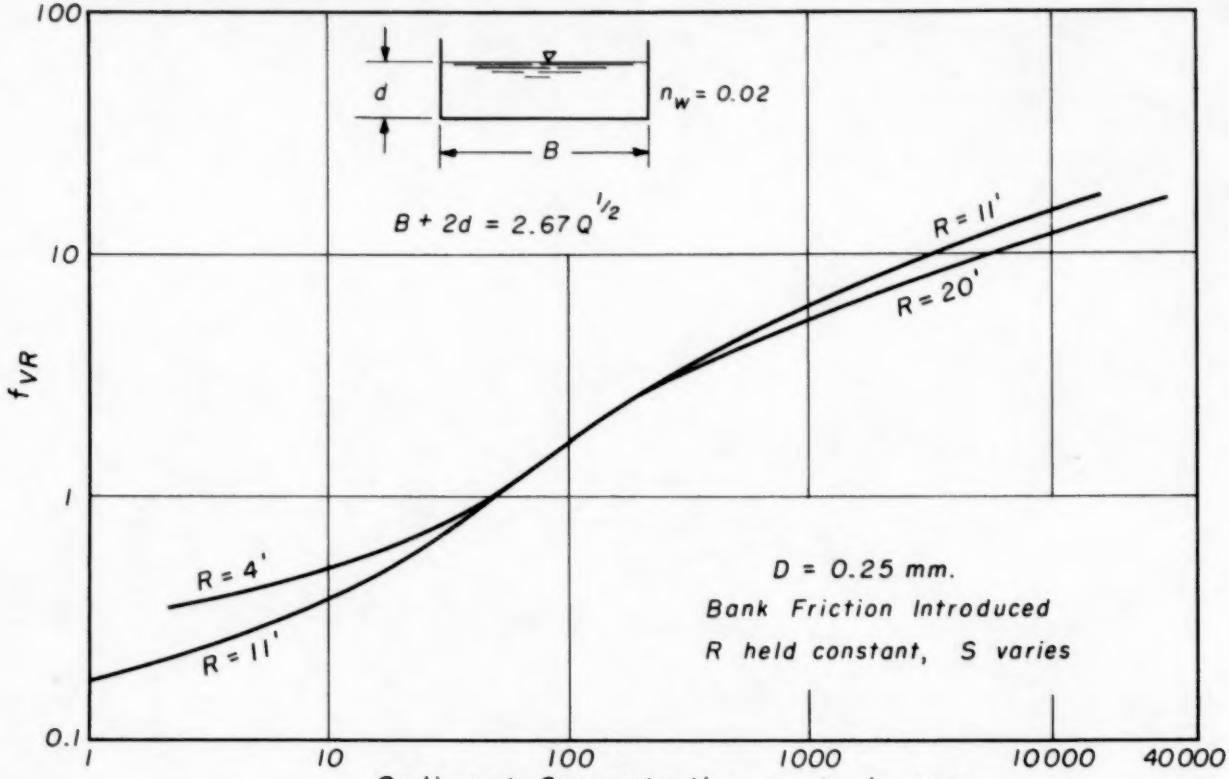


Fig. 6 Relationship Between $f_{VR}$ and Sediment Concentration With Bank Friction Introduced

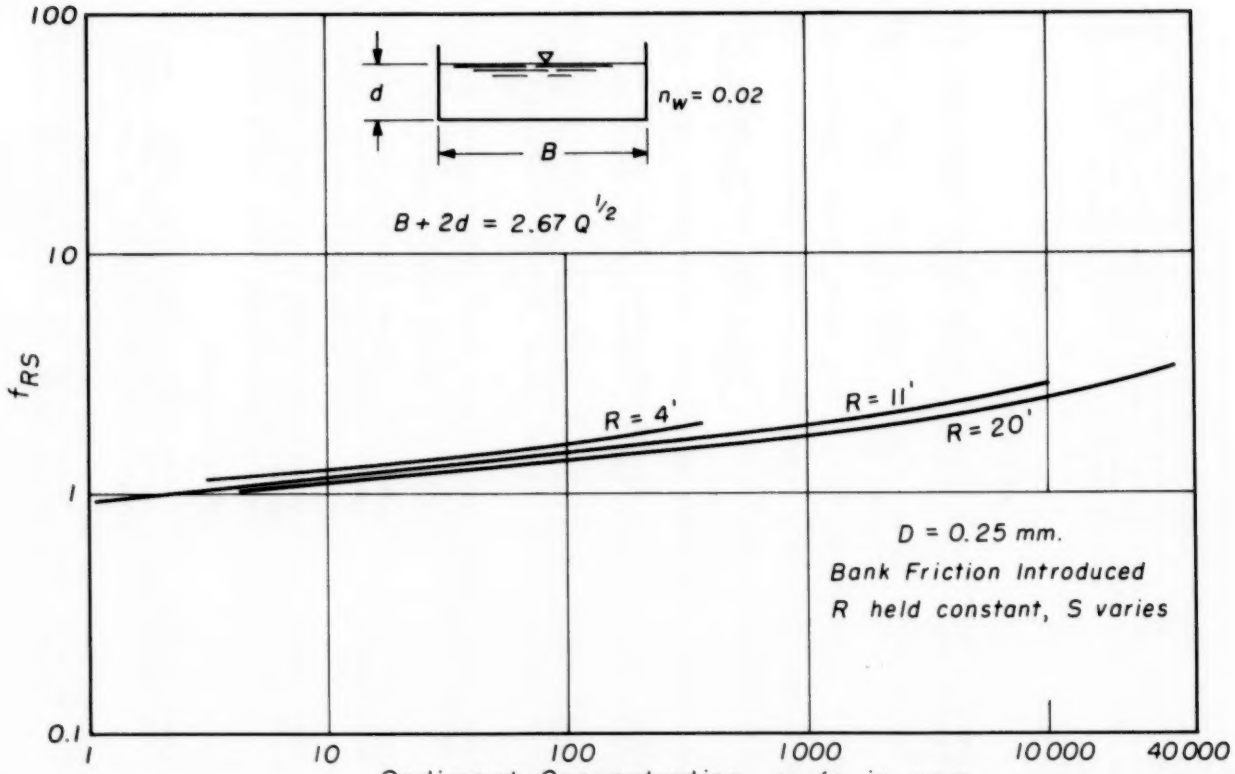


Fig. 7 Relationship Between $f_{RS}$ and Sediment Concentration With Bank Friction Introduced

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c. Discussion of several papers, grouped by Divisions.
d. Presented at the Atlanta (Ga.) Convention of the Society in February, 1954.
e. Presented at the Atlantic City (N.J.) Convention in June, 1954.

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